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EXOTIC PENTAQUARKS, CRYPTO-HEPTAQUARKS AND LINEAR THREE-HADRONIC MOLECULES

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In this talk, multiquarks are studied microscopically in a standard quark model. In pure ground-state pentaquarks the short-range interaction is computed and it is shown to be repulsive, a narrow pentaquark cannot be in the groundstate. As a possible excitation, an additional quark-antiquark pair is then considered, and this is suggested to produce linear molecular system, with a narrow decay width. This excitation may be energetically favourable to the p-wave excitation suggested by the other pentaquark models. Here, the quarks assemble in three hadronic clusters, and the central hadron provides stability. The possible crypto-heptaquark hadrons with exotic pentaquark flavours are studied.

Exotic multiquarks are expected since the early works of Jaffe [1], and the masses and decays in the SU(3) exotic anti-decuplet were first predicted within the chiral soliton model [2]. The pentaquarks have been revived recently by several searches of the $\Theta^+(1540)$ [3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20], first discovered at LEPS [3], and by searches of the $\Xi^{--}(1860)$ [21,22,23] and of the $D^{*-}p(3100)$ [24], observed respectively at NA49 [21] and at H1 [24]. Pentaquark structures have also been studied on the lattice [25,26,27,28,29,30,31,32]. Moreover multiquarks are favoured by the presence of several different flavours [33,34,35]. The observation of the $D^{*-}p(3100)$ at H1, the observation of double-charmed baryons at SELEX [36], and the future search of double-charmed baryons at COMPASS [37] suggest that new pentaquarks with heavy quarks may be discovered.

In this talk it is shown that the pentaquarks cannot be in the groundstate. The lowest excitation consists in including a light quark-antiquark pair in the system. This results in a heptaquark and in a linear molecular system. The possible crypto-heptaquark hadrons with exotic pentaquark

flavours, with strange, charmed and bottomed quarks, are studied. Recently this principle was used to suggest that the $\Theta^+(1540)$ is a $K \bullet \pi \bullet N$ molecule with binding energy of 30 MeV [38,39,40], and the $\Xi^{--}(1862)$ is a $\bar{K} \bullet N \bullet \bar{K}$ molecule with a binding energy of 60 MeV [38,41]. I also suggest that the new positive parity scalar $D_s(2320)$ and axial $D_{s+}(2460)$ are $\bar{K} \bullet D$ and $\bar{K} \bullet D^*$ multiquarks [42], and that the $D^{*-}p(3100)$ is consistent with a $D^* \bullet \pi \bullet N$ linear molecule with an energy of 15 MeV above threshold [38,43]. A systematic search of similar structures has also been performed [44]. These recent results are now reviewed.

Here I study multiquarks microscopically with a standard quark-model (QM) Hamiltonian. The energy of the multiquark state, and the short range interaction of the mesonic or baryonic subclusters of the multiquark are computed with the multiquark matrix element of the QM Hamiltonian,

$$H = \sum_i T_i + \sum_{i<j} V_{ij} + \sum_{i\bar{j}} A_{i\bar{j}} \ . \tag{1}$$

Each quark or antiquark has a kinetic energy T_i. The colour-dependent two-body interaction V_{ij} includes the standard confining and hyperfine terms,

$$V_{ij} = \frac{-3}{16} \vec{\lambda}_i \cdot \vec{\lambda}_j \left[V_{conf}(r) + V_{hyp}(r) \vec{S}_i \cdot \vec{S}_j \right] \ . \tag{2}$$

The potential of eq. (2) reproduces the meson and baryon spectrum with quark and antiquark bound states (from heavy quarkonium to the light pion mass). Moreover, the Resonating Group Method (RGM) [45] was applied by Ribeiro, [46] Toki [47] and Oka [48] to show that in exotic $N + N$ scattering the quark two-body-potential, together with the Pauli repulsion of quarks, explains the $N + N$ hard core repulsion. Recently, a breakthrough was achieved in chiral symmetric quark models. These models are inspired in the original work of Nambu and Jona-Lasinio [49]. Addressing a tetraquark system with $\pi + \pi$ quantum numbers, it was shown that the QM with the quark-antiquark annihilation $A_{i\bar{j}}$ also fully complies with chiral symmetry, including the Adler zero and the Weinberg theorem [50,51,52].

For the purpose of this talk, only the matrix elements of the potentials in eq. (1) matter. The hadron spectrum constrains the hyperfine potential,

$$\langle V_{hyp} \rangle \simeq \frac{4}{3} \left(M_\Delta - M_N \right) \simeq M_{K^*} - M_K \ . \tag{3}$$

The pion mass [53], constrains the annihilation potential,

$$\langle A \rangle_{S=0} \simeq -\frac{2}{3} (2M_N - M_\Delta) \ , \tag{4}$$

and this is correct for the annihilation of u or d quarks.

The annihilation potential only shows up in non-exotic channels, and it is clear from eq. (4) that the annihilation potential provides an attractive (negative) interaction. The quark-quark(antiquark) potential is dominated by the interplay of the hyperfine interaction of eq. (3) and the Pauli quark exchange. In s-wave systems with low spin this results in a repulsive interaction. Therefore, I arrive at the attraction/repulsion criterion for groundstate hadrons:

- *whenever the two interacting hadrons have quarks (or antiquarks) with a common flavour, the repulsion is increased by the Pauli principle;*
- *when the two interacting hadrons have a quark and an antiquark with the same flavour, the attraction is enhanced by the quark-antiquark annihilation.*

For instance, $uud - s\bar{u}$ is attractive, and $uud - u\bar{s}$ is repulsive. This qualitative rule is confirmed by quantitative computations of the short-range interactions of the π, N, K, D, D^*, B, B^* [38,42,43,41,50,51,52].

The attraction/repulsion criterion shows clearly that the exotic groundstate pentaquarks, containing five quarks only, are repelled. If the pentaquark could be forced to remain in the groundstate, this repulsion would provide a mass of 1535 MeV, close to the Θ^+ mass. There is an evidence of such a negative parity state both in quark model calculations and in lattice computations. However the existence of this groundstate can only appear as an artifact in simulations that deny the decay into the $K - N$ channel. Actually the groundstate is completely open to a strong decay into the $K - N$ channel, and this decay is further enhanced by the repulsion. It is indeed well known that any narrow pentaquark must contain an excitation, to prevent a decay width of hundreds of MeV to a meson-baryon channel. This is understood in the diquark and string model of Jaffe and Wiczek [54] and Karliner and Lipkin [55], and in the Skyrme model of Diakonov, Petrov and Polyakov [2]. These models suggest that the pentaquarks include a p-wave, or rotational excitation. However this excitation usually leads to a higher energy shift than the one observed, and a novel energy cancellation remains to be consistently provided. A candidate for the energy cancellation is the flavour-hyperfine interaction of Stancu and Riska [56]. Although these models are quite appealing, and they have been advocating pentaquarks for a long time, here I propose a different mechanism, which is more plausible in a standard quark model approach. Moreover this mechanism is in a sense confirmed in recent lattice computations, where pentaquarks with p-wave excitations indeed have a higher mass than the observed pentaquarks.

Table 1. Exotic-flavour pentaquarks with no heavy quark.

flavour	linear molecule	mass [GeV]	decay channels
$I=1/2,\ ssss\bar{l}(+3\,l\bar{l})$:	five-hadron molecule		
$I=1,\ sssl\bar{l}(+2\,l\bar{l})$:	four-hadron molecule		
$I=3/2,\ ssll\bar{l}(+l\bar{l})=$	$s\bar{l}\bullet lll\bullet s\bar{l}$: $\bar{K}\bullet N\bullet\bar{K}=\mathbf{\Xi}^{--}$	*1.86*	$\bar{K}+\Sigma,\ \pi+\Xi$
$I=2,\ slll\bar{l}(+l\bar{l})=$	$s\bar{l}\bullet lll\bullet l\bar{l}$:	pion unbound	
$I=5/2,\ llll\bar{l}(+l\bar{l})=$	$l\bar{l}\bullet lll\bullet l\bar{l}$:	pion unbound	
$I=0,\ llll\bar{s}(+l\bar{l})=$	$l\bar{s}\bullet l\bar{l}\bullet lll$: $K\bullet\pi\bullet N=\mathbf{\Theta}^{+}$	*1.54*	$K+N$

In this talk I consider that a s-wave flavour-singlet light quark-antiquark pair $l\bar{l}$ is added to the pentaquark M. The resulting heptaquark M' is a state with parity opposite to the original M [57], due to the intrinsic parity of fermions and anti-fermions. The ground-state of M' is also naturally rearranged in a s-wave baryon and in two s-wave mesons, where the two outer hadrons are repelled, while the central hadron provides stability. Because the s-wave pion is the lightest hadron, the minimum energy needed to create a quark-antiquark pair can be as small as 100 MeV. This energy shift is lower than the typical energy of 300-600 MeV of spin-isospin or angular excitations in hadrons. Moreover, the low-energy p-wave decay of the heptaquarks M' (after the extra quark-antiquark pair is annihilated) results in a very narrow decay width, consistent with the observed exotic flavour pentaquarks.

I now detail the strategy to find the possible linear heptaquark molecules, neglecting higher Fock space excitations.

a) The top quark is excluded because it is too unstable. To minimise the short-range repulsion and to increase the attraction of the three-hadron system, I only consider pentaquarks with a minimally exotic isospin, and with low spin.

b) Here the flavour is decomposed in an s-wave system of a spin 1/2 baryon and two pseudoscalar mesons, except for the vectors D^* and B^* which are also considered.

c) I consider as candidates for narrow pentaquarks systems where one hadron is attracted by both other ones. The criterion is used to discriminate which hadrons are bound and which are repelled.

Table 2. Exotic flavour pentaquarks with one heavy quark.

flavour	linear molecule	mass [GeV]	decay channels
$I=1/2, Hsss\bar{l}(+2\,l\bar{l})$:	four-hadron molecule		
$I=1, Hssl\bar{l}(+l\bar{l})=$	$s\bar{l}\bullet llH\bullet s\bar{l}$:		
	$\bar{K}\bullet\Lambda_c\bullet\bar{K}$	3.23 ± 0.03	$\bar{K}+\Xi_c,\,\pi+\Omega_c$
	$\bar{K}\bullet\Lambda_b\bullet\bar{K}$	6.57 ± 0.03	$\bar{K}+\Xi_b,\,\pi+\Omega_b$
$I=3/2, Hsll\bar{l}(+l\bar{l})=$	$s\bar{l}\bullet lll\bullet H\bar{l}$:		
	$\bar{K}\bullet N\bullet D$	3.25 ± 0.03	$\bar{K}+\Sigma_c,\,D+\Sigma,\,\pi+\Xi_c$
	$\bar{K}\bullet N\bullet D^*$	3.39 ± 0.03	$\bar{K}+\Sigma_c,\,D^*+\Sigma,\,\pi+\Xi_c$
	$\bar{K}\bullet N\bullet\bar{B}$	6.66 ± 0.03	$\bar{K}+\Sigma_b,\,\bar{B}+\Sigma,\,\pi+\Xi_b$
	$\bar{K}\bullet N\bullet\bar{B}^*$	6.71 ± 0.03	$\bar{K}+\Sigma_b,\,\bar{B}^*+\Sigma,\,\pi+\Xi_b$
$I=2, Hlll\bar{l}(+l\bar{l})=$	$l\bar{l}\bullet lll\bullet H\bar{l}$:	pion unbound	
$I=1/2, Hlll\bar{s}(+l\bar{l})=$	$l\bar{s}\bullet l\bar{l}\bullet llH$:		
	$K\bullet\pi\bullet\Sigma_c$	3.08 ± 0.03	$K+\Lambda_c,\,K+\Sigma_c,\,D_s+N$
	$K\bullet\pi\bullet\Sigma_b$	6.41 ± 0.1	$K+\Lambda_b,\,K+\Sigma_b,\,D_s+N$
$I=1/2, Hlll\bar{s}(+l\bar{l})=$	$l\bar{s}\bullet H\bar{l}\bullet lll$:		
	$K\bullet\bar{D}\bullet N$	3.25 ± 0.03	$K+\Lambda_c,\;K+\Sigma_c,\;D_s+N$
	$K\bullet\bar{D}^*\bullet N$	3.39 ± 0.03	$K+\Lambda_c,\;K+\Sigma_c,\;D_s^*+N$
	$K\bullet\bar{B}\bullet N$	6.66 ± 0.03	$K+\Lambda_b,\;K+\Sigma_b,\;B_s+N$
	$K\bullet\bar{B}^*\bullet N$	6.71 ± 0.03	$K+\Lambda_b,\;K+\Sigma_b,\;B_s^*+N$

d) In the case of some exotic flavour pentaquarks, only a four-hadron-molecule or a five-hadron-molecule would bind. These cases are not detailed, because they are difficult to create in the laboratory.
e) Moreover, in the particular case where one of the three hadrons is a π, binding is only assumed if the π is the central hadron, attracted both by the other two ones. The π is too light to be bound by just one hadron [38].
f) The masses of the bound states with a pion are computed assuming a total binding energy of the order of 10 MeV, averaging the binding energy of the Θ^+ and of the $D^{*-}p$ system in the molecular perspective. The masses of the other bound states are computed assuming a total binding energy of the order of 50 MeV, averaging the binding energies of the Ξ^{--} and of the new positive-parity D_S mesons.
g) This results in an error bar of $\pm$ 30 MeV for the mass. When one of the three hadrons is not listed by the Particle Data Group [58], its mass is extracted from a lattice computation [59], and the error bar is $\pm$ 100 MeV.
e) Although three-body decay channels are possible through quark rearrangement, their observation requires high experimental statistics. Only some of the different possible two-body decay processes are detailed here.

Table 3. Exotic flavour pentaquarks with one heavy anti-quark.

flavour	linear molecule	mass [GeV]	decay channels
$I=0, ssss\bar{H}(+3l\bar{l})$:	five-hadron molecule		
$I=1/2, sssl\bar{H}(+2\,l\bar{l})$:	four-hadron molecule		
$I=0, ssll\bar{H}(+l\bar{l}) =$	$l\bar{H}\bullet l\bar{l}\bullet lss$		
	$\bar{D}\bullet\pi\bullet\Xi$	3.31 ± 0.03	$\bar{D}+\Xi,\ \bar{D}_s+\Lambda$
	$\bar{D}^*\bullet\pi\bullet\Xi$	3.45 ± 0.03	$\bar{D}^*+\Xi,\ \bar{D}_s^*+\Lambda,\ \bar{D}_s+\Lambda$
	$B\bullet\pi\bullet\Xi$	6.73 ± 0.03	$B+\Xi,\ B_s+\Lambda$
	$B^*\bullet\pi\bullet\Xi$	6.77 ± 0.03	$B^*+\Xi,\ B_s^*+\Lambda,\ B_s+\Lambda$
$I=1/2, slll\bar{H}(+l\bar{l}) =$	$l\bar{H}\bullet l\bar{l}\bullet lls$		
	$\bar{D}\bullet\pi\bullet\Sigma$	3.19 ± 0.03	$\bar{D}+\Lambda,\ \bar{D}+\Sigma,\ \bar{D}_s+N$
	$\bar{D}^*\bullet\pi\bullet\Sigma$	3.33 ± 0.03	$\bar{D}^*+\Lambda,\ \bar{D}^*+\Sigma,\ \bar{D}_s^*+N$
	$B\bullet\pi\bullet\Sigma$	6.60 ± 0.03	$B+\Lambda,\ B+\Sigma,\ B_s+N$
	$B^*\bullet\pi\bullet\Sigma$	6.64 ± 0.03	$B^*+\Lambda,\ B^*+\Sigma,\ B_s^*+N$
$I=1/2, slll\bar{H}(+l\bar{l}) =$	$l\bar{H}\bullet s\bar{l}\bullet lll$		
	$\bar{D}\bullet\bar{K}\bullet N$	3.25 ± 0.03	$\bar{D}+\Lambda,\ \bar{D}+\Sigma,\ \bar{D}_s+N$
	$\bar{D}^*\bullet\bar{K}\bullet N$	3.39 ± 0.03	$\bar{D}^*+\Lambda,\ \bar{D}^*+\Sigma,\ \bar{D}_s^*+N$
	$B\bullet\bar{K}\bullet N$	6.66 ± 0.03	$B+\Lambda,\ B+\Sigma,\ B_s+N$
	$B^*\bullet\bar{K}\bullet N$	6.71 ± 0.03	$B^*+\Lambda,\ B^*+\Sigma,\ B_s^*+N$
$I=0, llll\bar{H}(+l\bar{l}) =$	$l\bar{H}\bullet l\bar{l}\bullet lll$		
	$\bar{D}\bullet\pi\bullet N$	2.93 ± 0.03	$\bar{D}+N$
	$\bar{D}^*\bullet\pi\bullet N = \mathbf{\bar{D}^{*-}p}$	*3.10*	$\bar{D}^*+N,\ \bar{D}+N$
	$B\bullet\pi\bullet N$	6.35 ± 0.03	$B+N$
	$B^*\bullet\pi\bullet N$	6.39 ± 0.03	$B^*+N, B+N$

To conclude, this work has performed a systematic search of exotic-flavour pentaquarks, using the heptaquark, or linear three-body hadronic-molecule perspective. This perspective is the result of standard QM computations of pentaquarks and hepatquark masses and of hadron-hadron short-range interactions. A large number of new exotic flavour-pentaquarks are predicted in Tables 1, 2 and 3 together with their two-body decay channels. The systems with more than one heavy antiquark are very numerous and they are omitted here. Moreover, some new multiquarks may be easier to bind than the presently observed exotic pentaquarks.

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